Independent Component Analysis (ICA) of GRACE-derived Australian Hydrological Signals

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Motivation

GRACE twin satellites are continuously providing valuable hydrological information highlighting its spatio-temporal mass variations and redistributions within the Earth system. This is achieved through:

1. The removal of the effect of the constant long-term gravity field.
2. Separation of the contribution of the atmosphere and the ocean to time variable gravity field using physical models.

Problems inherent to the use of gravity for sensing of hydrological variation using the approach above are:

- From the data alone, one cannot separate signals that are caused by different physical processes.
- The problem with these physical models is that they are not perfect considering the accuracy of the GRACE products.
- The integral scheme of the GRACE mass signals (related to the different compartments, e.g., atmosphere, ocean, Earth's surface and its interior) also makes the meaningful signal extraction procedure a challenging signal separation problem.

This therefore necessitates the need for new methods for pattern extraction that are essential to explore the concepts of physical processes and also to monitor water resources, which is the focus in this study. Using a simulation and also real GRACE, hydrological model (WGHM) and rainfall (TRMM) data sets, we show that involving higher order statistical moments in the frame of Independent Component Analysis (ICA) algorithm, localizes the weaker Australian hydrological signals from the surrounded oceanic mass sources.

Methods

Principle Components Analysis (PCA)

PCA method seeks a set of optimal orthogonal base-functions to explain a maximum amount of variance in the data set based on eigenvalue decomposition of the auto-covariance matrix of a centered data set (Lorenz, 1956).

$$\overline{\mathrm{X}}\,(\mathrm{t},\mathrm{s}) = \mathrm{P}^{*}\,\mathrm{E}^{T}$$

P^*: the temporal components (PCs),
E: the spatial eigenvectors (EOFs), normalized to unit length in its columns.

Independent Component Analysis (ICA)

ICA incorporates more information from the probability density function (pdf) underlying data (Forootan and Kusche, 2011-sub):

Step1
PCA decomposition: $\mathbf{X_j} = \mathbf{P}_j^*\mathbf{E}_k^T$.

Step2
Computing fourth order cumulants ($\mathbf{Q_x}^*$), using the orthogonal eigenvectors (EOFs) from Step1.

Matrix $\mathbf{Q_x}$ needed for planner rotation in Step4.

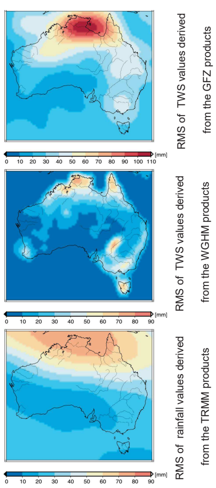
Step3
PCA decomposition of $\mathbf{Q_x}^*$ from Step2 to provide the initial starting values of the rotation matrix $\mathbf{R_k}$ needed for the iteration in Step4.

Step4
Planar rotation using $\mathbf{Q_x}^*$ from Step2 and $\mathbf{R_k}$ from Step3. The proper $\mathbf{R_k}$ which diagonalize $\mathbf{Q_x}^*$ is then computed iteratively.

Main computing equation of ICA
$\mathbf{R_k}$ from Step4 is used to rotate the selected EOFs to isolate the signals: $\mathbf{X_j} = \mathbf{P}_j^*\mathbf{R_j}\mathbf{R}_j^T\mathbf{E}_j^T$.

Data sets

- Three sets of the GRACE DDK2 (Kusche et al. 2009) filtered products. The data is converted to 1×1 degree, gridded total water storage (TWS) fields using all available solutions of the GFZ (October 2002 to May 2011), CSR (October 2002 to May 2011) and ITG2010 (August 2002 to August 2009) Bonn centers.
- Water Gap Hydrological model (WGHM), 0.5×0.5 degree TWS products from 2000 to 2010.
- Tropical Rainfall Measuring Mission (TRMM) level 3B, 0.25×0.25 degree re-anlaised rainfall products from January 2002 to May 2011.



References

- E. Forootan, J. Kusche (2011, submitted). Separation of global time-variable gravity signals into maximally independent. J. Geodesy.
- J. Kusche et al. (2009). Decorrelated GRACE time-variable gravity solutions by GFZ, and their validation using a hydrological model, J.Geodesy, 83, 903-913.
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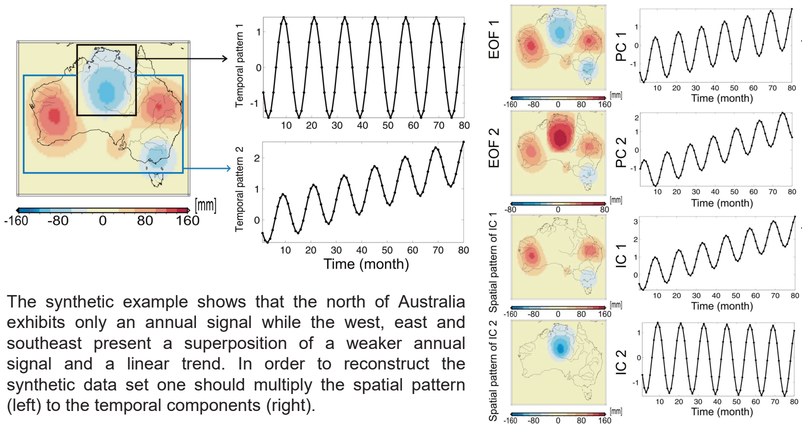
Synthetic Example

Rationale: to investigate whether ICA correctly separates components, at least when the mixture is caused by linear super-position of different signals. This result encouraged us to study ICA on the real TWS dataset from GRACE.

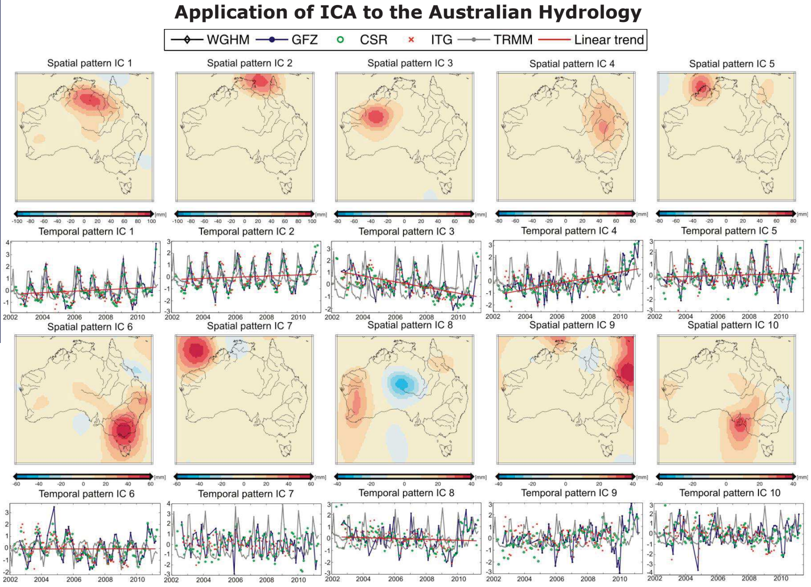


The synthetic example shows that the north of Australia exhibits only an annual signal while the west, east and southeast present a superposition of a weaker annual signal and a linear trend. In order to reconstruct the synthetic data set one should multiply the spatial pattern (left) to the temporal components (right).

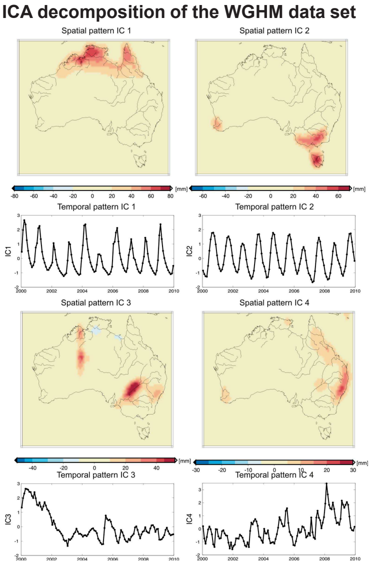
Results

- ✓ PCA failed to separate the true signals with showing a mixed behaviour in all regions.
- ✓ ICA truly recovered the predefined signals. The results indicate that rotating the PCA's base-functions toward independency helps to solve the signal separation problem in the superposition case.

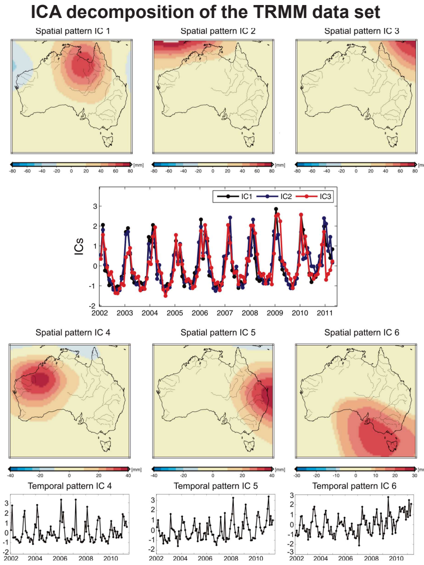
Application of ICA to the Australian Hydrology



ICA decomposition of the WGHM data set



ICA decomposition of the TRMM data set



ICA analysis of GRACE:

IC1: Annual hydrological signal over the northern Australia.

IC2: Indicates the annual monsoonal rainfall effect.

IC3: Mass loss over the northwestern Australia, whose cause in uncertain.

IC4: Inter-annual fluctuations along with recent flood trend over the east and northeast.

IC5: Annual cycle mainly over the northwestern region, mainly originated from the ocean.

IC6: Mass changes over the southeast showing a significant loss in 2005-2006 due to drought.

IC7: S2 aliasing effect.

IC8: Mass loss over the west and gain in central regions.

IC9: The effect of recent floods over the ocean in the east.

IC10: Mass changes mainly over the lower Murray-Darling basin.

ICA Analysis of WGHM:

IC1 and IC2: Annual mass change over the north and south Australia.

IC3: water loss over the northwest and lower Murray-Darling basin.

IC4: Inter-annual fluctuations over the east and northeast regions.

ICA Analysis of TRMM:

IC1, IC2 and IC3: Main annual rainfalls over the northern regions.

IC4: Decreasing the amount of precipitation over the west Australia, mainly during 2005 and the years after 2006.

IC5 and IC6: Recent increasing of the precipitation mainly over the eastern Australia.

Discussion and Conclusion

- Using a simulation we showed that how incorporating non-Gaussian statistical information in the frame of ICA improves the decomposition of the GRACE time variable signals.
- ICA showed more localized patterns and significantly reduced the PCA's mixing problem.
- The suitability of ICA for processing the weaker hydrological signals of Australia is also proved with providing physically interpretable components.
- The presented algorithm was also successful to isolate the oceanic signal from the land.
- The impact of the 2006-2007 drought on Australian water resource is clearly identified in the southern-Australia, Murray Darling Basin and the Western Australia regions, whereas the eastern part of Australia shows mass gain from 2010 which would be related the current flood in the region.
- The comparison of the GRACE ICA components with WGHM and TRMM showed a good agreement.
- WGHM, except for the northern dominant annual cycle, underestimated the magnitude of the hydrological signal. This was evident in the IC4, IC5 and IC6 of the GRACE products.
- Based of the derived results, we recommend investigating the presented ICA algorithm for other hydrological case studies.

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